OVERVIEW OF THE DEVELOPMENT OF WATER-MIST SYSTEMS FOR US NAVY SHIPS

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ABSTRACT

During the past 20 years. the US Navy has undertaken an extensive evaluation *of* water mist for fire protection applications aboard ship. Both small and full-scale tests have heen conducted to study water mist as a replacement for Halon 1301 and to explore the possible use of mist in lieu of conventional sprinklers. Tests have been conducted at the David Taylor Ship Research and Development Center in Annapolis, MD. at the Naval Research Laboratory. Chesapeake Division. and aboard the Navy's fire research vessel. the ex-USS Shadwell in Mobile. AI.. Engineering analysis and trade-off studies have been conducted to compare ship impact (cost, space, and weight) of water mist versus halon and other gaseous alternatives. During recent testing at the Applied Physics Laboratory of Johns Hopkins University. energized electrical equipment (standard shipboard switchboards. electric motors, and motor controllers) were exposed to water mist at a flux density of 0.67 Lpm/m^3 (0.005 gpm/ft^3) to assess potential effects on equipmcnt and possible personnel shock hazards.

As a result of the testing and analysis completed thus fir. the Navy has specified water mist to protect the propulsion machinery spaces on the Navy's next new ship. the LPD-17. currently undergoing final design at Avondale Industries. Later this year. live tire exercises will he conducted with fleet personnel to refine the doctrine and tactics for use of water mist on the LPD-17. Testing is now underway to explore the use of water mist in miscellaneous spaccs containing flammable liquid hazards, such as flammable liquid storerooms, paint issue rooms, diesel generator spaces. and fuel pump rooms. This evaluation is considering commercially available self-contained water mist systems. as well as a pumped system utilizing seawater supplied by the firemain system. Water mist is also being evaluated as part of the Damage Control-Automation for Reduced Manning (DC-ARM) program. The DC-ARM program is a multiyear *effort* sponsored by the Office of Naval Research to develop automated damage control systems to enhance the survivability of future surface combatants and to compensate for anticipated Navy-wide reductions in fleer manning levels. Under DC-ARM. water mist is being considered as a possible total-ship protection method as well as for selected applications *for* tlashover supprcssion in shipboard compartments and as a means of boundary cooling.

PURPOSE

The purpose of this paper is threefold:

- Provide an historical summary of the development of Navy shiphoard water-mist systems
- Present a consolidated list of all pertinent references for Navy shipboard water-mist research and development efforts
- Outline future water mist research plans

CHRONOLOGICAL SUMMARY OF RESEARCH

Initial Studies (1978-1980)

The potential benefits of water mist for Navy fire protection applications were presented in two Navy papers published over 20 years ago [1,2]. These papers offered calculations that illustrated how small water droplets, as contained in "water fog" or "fine water spray," could achieved fire extinguishment by gas phase cooling. During the next two years, experiments at the David Taylor Ship Research & Development Center validated the theoretical calculations during efforts to develop innovative concepts for extinguishing fires in submarines [3,4,5]. Mist was generated by commercial impingement pin type (Bete P80) atomizing nozzles operated at discharge pressures of 17-27 bar (250-400 psi). Droplets were estimated to measure in the 80-100 micron range. Modest success was achieved in extinguishing flammable liquid pan fires in simulated submarine machinery spaces and torpedo storage rooms. The proposed system consisted of an array of overhead nozzles fed by a rechargeable potable water pressure tank. Though never adopted by the Navy for submarine use, the program confirmed the efficacy of water mist for fire extinguishment and rapid cooling.

Small-Scale Testing (1990-1994)

Due to the wide spread acceptance of Halon 1301 for various shipboard fire protection applications, interest in water mist languished in the 1980s. However, by 1990, the identification of halon as a destroyer of stratospheric ozone and the subsequent establishment of a halon production phaseout via the Montreal protocol stimulated new interest in water mist as a potential halon alternative [6]. A multiyear water-mist research and development program was initiated with small-scale testing at the Naval Research Laboratory-Chesapeake Beach Detachment (NRL-CBD) in a 3 by 3 by 2.4 m (10 by 10 by 8 ft) steel compartment. Mist was generated by generic systems utilizing modified industrial spray nozzles as well as commercially available water-mist hardware. Fire scenarios included both obstructed and unobstructed Class A wood crib fires and Class B spray and pool fires. The parameters varied: fire size and location, nozzle spacing, mist application rates, mist characteristics (spray pattern, drop momentum, drop size distribution), ventilation, degree of obstructions, comer effects, and oxygen depletion. These scoping tests produced some general observations relative to the performance of water mist [7-11].

- Large fires are easier to extinguish than small fires, due mainly to the displacement of oxygen by the expansion of the water mist to steam.
- Obstructed fires become more difficult to extinguish with increased water droplet horizontal travel distance (approximately 0.6 m being the limiting case for overhead downwardly discharging nozzles).
- Obstructed fires located in areas of low mist concentration, such as high in comers. are difficult to extinguish.
- Well-ventilated fires are difficult, but not impossible, for water mist and mist performs superior to gases in well-ventilated scenarios.
- Deep-seated Class A fires are difficult to extinguish totally, though surface flaming is suppressed.
- Mist enhances room tenability by cooling and smoke scrubbing.
- Even worst case highly obstructed fires become self-limiting in size (above a threshold heat release rate the fires are extinguished by oxygen depletion due to generation of saturated water vapor).
- Water-mist systems have relatively low water demand (fires typically extinguished at a volumetric density of 0.17-1.7 Lpm/m^3 (0.0013-0.0125 gpm/ft^3).
- Carbonate additives can make a measurable improvement to fire extinguishment, hut introduce potential toxicity and corrosivity concerns.

In addition to the small-scale tests at NRL-CBD. the Navy sponsored small-scale tests at Denver Research Institute to evaluate the ability of water mist to attenuate hydrogen/air explosions [12]. These tests were undertaken because of concern surrounding the generation of hydrogen by the propulsion engine of a proposed new torpedo. The testing showed that a viable explosion suppression system could be achieved with water mist, provided there is time available prior to the explosion to reach *a* mist concentration of at least 0.7 L/m^3 (0.0052 gal/ft^3).

Full-Scale Tests

Following successful completion of the small-scale test program, full-scale tests were conducted to develop fundamental water-mist system design parameters for protecting ship machinery spaces. Most of these tests were conducted aboard the Navy's fire research vessel, the ex-USS Shadwell in Mobile, AL [13-20]. Similar tests, applicable to flammable storerooms and machinery spaces on US Army boats, were conducted under Army sponsorship at NKL-CBD [21,22,23].

The ex-USS Shadwell tests were run in *a* two-level compartment having *a* gross volume of 960 m^3 (36,000 ft^3). Test fires were as large as 10 MW and consisted of a combination of open fuel sprays. shielded sprays. and pan fires involving both heptane and diesel fuel. Trails were run to compare performance of mist in an unobstructed space versus a space with numerous obstructions. For obstructed space scenarios, full-scale mock-ups of a simulated diesel engine, reduction gear, gas turbine, and associated supply and exhaust ducts were installed. Some tests were run with the ventilation running so as to simulate typical Navy machinery space air exchange rates (about 20 air changes/hr). Water-mist systems evaluated consisted of single fluid high pressure, single tluid low pressure and twin fluid (water/air or water/nitrogen). The major findings of the ex-USS Shadwell tests were as follows:

- The best performing water mist nozzle was a modified spraying systems company Model 7N nozzle (with 7 model 1/4 LN discharge tips per nozzle) flowing at 70 bar (1000 psi).
- Performance was best when nozzles were installed at the overhead of each level.
- Recommended nozzle spacing was nominally 2.5 m (8 ft) apart with sufficient nozzles to produce a total water flow of 0.4 Lpm/m^3 (0.003 gpm/ft^3).
- Extinguishment times were typically less than 1 min. except for small obstructed fires or for cases where forced ventilation was deliberately left running.
- Compartment temperatures dropped from 500 to 50 °C within seconds after mist was activated.
- Overall conclusion was that water mist was *a* viable alternative to **Halon** 1301 for protecting Navy machinery spaces.

LPD-17 Design and Validation

After a thorough review of the results of the full-scale tests, the Naval Sea Systems Command decided to install water mist for fire protection in the propulsion machincry spaces of the next new Navy ship, the LPD-17 [24]. The engineering challenge was to convert a generic system into a specific design suitable for the unique arrangement of machinery spaces on the LPD-17. A feasibility study and preliminary design was conducted by a marine engineering consulting firm using the ex-USS Shadwell results as the baseline for performance [25]. This study included tradeoff analysis of alternative designs for water storage, pressure generation, controls, valving, and piping. A system architecture was selected that minimized ship installation cost, space, and weight impact while assuring adequate performance and life cycle reliability. survivability, and maintainability. The resulting design for LPD-17 consisted of two water-mist pumping stations, one forward on the port side and the other aft on the starboard side. Each pumping station consisted of a dedicated potable water storage tank (with a 15 min supply) and a 200 HP electric motor-driven, high-pressure positive displacement pump. A stainless steel water mist firemain was designed to pass through all five machinery spaces with a remote-controlled valving arrangement to allow mist to be delivered to any machinery space from either pump station [26,27].

A parallel study was conducted to optimize the design of the water-mist nozzle [28]. A prototype of the proposed LPD-17 system was installed on the ex-USS Shadwell and a complete series of fire extinguishment and system operational shake-down tests was performed [29,30] to validate the design. Following successful testing on ex-USS Shadwell, design lessons learned were generated for incorporation into the LPD-17 final ship design being performed by the designated shipbuilder, Avondale Industries in New Orleans, LA [31,32].

Numerical Modeling and Theoretical Studies

In addition to the applied research efforts to develop water mist for specific shipboard applications, the Navy has also performed or sponsored more basic research to establish a scientifically based understanding of the various mechanisms by which water mist suppresses fire. Several papers involving numerical modeling and theoretical studies have been published. Ndubizu et al. [33] report results of efforts to develop laboratory-scale experiments to generate data for the validation of a numerical model of a gaseous fuel diffusion flame for use as a baseline to evaluate mist extinguishment. A related computational study for optimizing water-mist injection characteristics for suppression of jet diffusion flames has also been released [34]. Though primarily concerned with the potential application of low-pressure water mist in residential occupancies, Prasad et al. [35] have fostered an understanding of how sensitive water-mist performance is to system operating pressure. Changes in operating pressure can affect drop size, initial drop momentum and application density.

One paper of note [36], which evolved from observations of steady state compartment temperatures in previous full-scale tests, presents a model for predicting the smallest fire within a known compartment geometry, which would produce sufficient water vapor to cause extinguishment via oxygen dilution. While this concept of critical fire size was recognized previously during full-scale tests of obstructed fires aboard ex-USS Shadwell, the paper offers a valuable quantitative predictive technique for determining maximum sustainable fire size within a misted space.

Water Mist on Electrical Equipment

The Navy sponsored a program at the Applied Physics Laboratory/Johns Hopkins University (APL/JHU) to evaluate the effects of water mist on energized electrical equipment. Equipment selected for testing consisted of three phase-450 VAC motors, motor controller, and switchboard, which were representative of equipment to be installed in the machinery spaces of LPD-17. The objective was to determine potential for equipment damage and to identify personnel electric shock hazards resulting from the discharge of mist onto energized equipment.

Mist was generated by the same nozzles specified for LPD-17. Overall application rate was about 60% higher than for LPD-17 to provide a margin of safety. Most tests were run with potable water, though a few tests were run with brackish and normal seawater to quantify differences due to salt content. Measurements of current leakage phase-to-phase and phase-to-enclosure were recorded as a function of mist exposure time. Results showed that the conductivity of salt-free potable water is very low. Shock hazards could only exist after a sustained mist flow, which results in plating out or pooling of water on equipmcnt surface. There was essentially no current leakage for motors or motor controllers. The shock hazard with switchboards is negligible if the boards are clean and properly grounded. The conclusion relative to LPD-I7 is that (I) the probability of creating a shock hazard is low and (2) watchstanders in the space would not have to evacuate prior to mist activation even if all equipment were energized.

Self-contained Water Mist

As a continuation of the program that developed water mist for the LPD-17 machinery space, a new initiative is underway at NRL-CBD to identify a small self-contained water-mist system for miscellaneous shipboard spaces, which in the past have been protected by Halon 1301. Included would he spaces such as tlammable liquid storerooms, paint issue rooms, emergency diesel generators, and fuel pump rooms. Bccause these spaces are small relative to machinery spaces and typically scattered throughout the ship, it would not be feasible to protect them with the same mist system specified for the machinery spaces.

A literature search was conducted to identify the performance characteristics and design features of available commercial off-the-shelf systems for this application [38]. A preliminary test plan has been prepared and testing *is* underway to evaluate selected commercial self-contained units incorporating pressurized water reservoirs [39]. Modified commercial systems will be tested if the off-the-shelfunits fail to give adequate performance or if they exhibit excessive ship impact in terms of cost. space. and weight. Additionally. the Naval Seal Systems Command has funded the design of a seawater mist system fed by a skid-mounted water-mist pump [40]. This system will draw water from the ship's firemain and may offer space and weight advantages over stored pressure units. Planning is underway to test the pumped seawater system later this year.

DC-ARM Ship-Wide Water Mist

The Office of Naval Research is sponsoring a multiyear effort to develop automated damage control systems to enhance the survivability of future surface combatants and to compensate for anticipated Navy-wide reductions in tleet manning levels. This program is entitled "Damage Control-Automation for Reduced Manning" (DC-ARM). Under DC-ARM water mist is being considered as a possible total-ship protection method as well as for selected applications for tlashover suppression in shipboard compartments and boundary cooling.

Testing conducted to date has shown that. in ventilation-limited spaces with low ceilings, flash-over suppression can be achieved with low water-mist application rates and widely spaced nozzles [41]. Even with nozzles installed only over doorways, maximum temperatures of 150 °C are possible. Achieving flashover suppression to a large degree also achieves boundary cooling because the compartment of fire origin does not become hot enough for heat to ignite materials in adjacent compartments. Additionally. tests have indicated that a water-mist nozzle placed over a doorway considerably interrupts the air flow in and out of the room and cools the gases that enter the corridor, thereby significantly reducing the smoke hazard.

FUTURE PLANS

The emphasis in this paper thus far has been water-mist research and development already accomplished. Several shipboard-related water mist efforts are on-going or proposed for future study. Future plans may be summarized as follows:

- Develop doctrine for use of water mist in LPD-17
- Extend the APL/JHU water-mist electrical equipment studies to include computers and typical electronics equipment
- Complete the evaluation of self-contained water mist systems
- Continue with water mist efforts under DC-ARM to develop the architecture for a ship-wide system

REFERENCES

1. Carhart, H. W., Fielding, G. H., and Williams, F. W., "Suppression - Why Not Water?," NRL Memorandum Report 3435, Naval Research Laboratory, Washington, DC, 1977.
2. Lugar, J. R., Fornsler, R. O., Carhart, H. W., and Fielding, G. H., "Flame Extinguishment by Waterfogs and Sprays," *Fifth Quadripartite Conference IEP* ***ABCA-7,*** Oct. 1978.
3. Lugar, J. R., *Water Mist Fire Protection,* David W. Taylor Naval Ship Research and Development Center, Bethesda, MD, 1979.
4. Lugar, J. R., *Preliminary Test Results of* ***Fine*** *Water Mist Fire Protection Systems Study,* David W. Taylor Naval Ship Research & Development Center, Bethesda, MD, 1979.
5. Lugar. J. R., *Status* ***Report*** *of Fine Water* ***Mist*** *Fire Protection,* David Taylor Naval Ship Research & Development Center, Bethesda, MD, 1980.
6. Hanauska, C. P., and Back, G. G., "Halons: Alternative Fire protection Systems, An Overview of Water Mist Fire Suppression Systems Technology," Hughes Associates, Inc., Columbia, MD, 1993.
7. Back, G. G., "Water Mist: Limits of the Current Technology for Use in Total Flooding Applications," presented for the Society of Fire Protection Engineers at the National Fire Protection Association Annual Meeting, May 1994.
8. Darwin, R. L.. "Large Scale Testing of Shipboard Halon Alternatives," *Proceedings,* Halon Alternatives Technical Working Conference, Albuquerque, NM, pp. 143-154, 1994.
9. Tatem, P. A., Beyler, C. L., DiNenno, P. J., Budnick, E. **K.,** Back, G. G., and Younis, S. E., **"A** Review of Water Mist Technology for Fire Suppression," NRL/MR/6180--94-7624, Washington, DC, Sept. 30, 1994.
10. Leonard, J. T., Back, G. G., and DiNenno, P. J., "Small/Intermediate Scale Studies of Water Mist Fire Suppression Systems," NRL Ltr Rpt Ser 6180/0869.1, Washington, DC, 29 Dec. 1994.
11. Leonard, J. T., and Back, G. G., "Revised Test Plan: Full-scale Testing of Total-flooding Water Mist Systems," NRL Ltr Rpt Ser 6180/0716.2, Washington, DC, 07 Oct. 1994.
12. Butz, J. **R.,** "Application of Fine Water Mists to Hydrogen Deflagrations," *Proceedings,* Halon Alternatives Technical Working Conference, Albuquerque, NM, pp. 345-355, 1993.
13. Leonard, J. T., and Back, G. G., " Revised Test Plan: Full-Scale testing of Total-Flooding Water Mist system," NRL Ltr Rpt Ser 6180/0716.2, 07 Oct. 1994.

14. Leonard. J. T., Back, G. G.. and DiNenno. P. J.. "Full Scale Machinery Space Water Mist Tests: Phase I - Unobstructed Space," NRL Ltr Rpt Ser 6180/0713.1, Washington, DC, Oct. 17, 1994.
15. Leonard, J. T., Back. G. G.. and DiNenno, P. J., " Full Scale Machinery Space Water Mist Tests: Phase II – Simulated Machinery Space." NRL Ltr Rpt Ser 6180/0868.2, Washington, DC, 23 Dec. 1994.
16. Darwin. R. L., Leonard, J. T., and Back. G. G., " Status Report on the Development of Water Mist Systems for US Navy Shipboard Machinery Space." *Proceedings*, Halon Options Technical Working Conference, Albuquerque, NM, pp. 411-422, 1995.
17. Leonard, J. T., Darwin, R. L., and Back. G. G., "Full Scale Tests of Water Mist Fire Suppression Systems for Machinery Spaccs," *Proceedings of the International Conference on Fire Research and Engineering,* D. P. Lund, Editor, Society of Fire Protection Engineers, 10-15 Sept. 1995.
18. Back, G. G., DiNenno. P. J., Leonard, J. T., and Darwin, R. L., " Full Scale Tests of Water Mist Fire Suppression Systems for Navy Shipboard Machinery Spaces: Phase 1 – Unobstructed Spaces,' 'NRL/MR/6180--96-7830, Washington. DC, Mar. 8, 1996.
19. Back. G. G., DiNenno, P. J., Leonard, J. T., and Darwin, R. L., "Full Scale Tests of Water Mist Fire Suppression Systems for Navy Shipboard Machinery Spaces: Phase II – Obstructed Spaces." NRL/MR/6180--96-7831, Washington, DC. Mar. 8. 1996.
20. Back, G. G. Darwin, R. L.. and Leonard. J. T., " Full Scale Tests of Water Mist Fire Suppression Systems for Navy Shiphoard Machincry Spaces," *Proceeding - at INTERFLAM 96, St. John's College, Cambridge, England*, 26 - 28 Mar. 1996.
21 Back. G. G., " An Experimental Evaluation of Water Mist Fire Suppression System Technologies Applied to Flammable Liquid Storeroom Applications," *Proceedings*, International Conference on Fire Research and Engineering, D. P. Lund, Editor, Society of Fire Protection Engineers, 10-15 Sept. 199.5.
22. Back, G. G., DiNenno. P. J., Hill, S. A., and Leonard. J. T., "Evaluation of Water Mist Fire Extinguishing Systems for Flammable Liquid Storeroom Applications on US Army Watercraft," NRL Ltr Rpt Ser 6180/0660.1, Washington, DC, 12 Oct. 1995.
23. Back, G. G., DiNenno. P. J.. Hill, S. A., and Leonard, J. T., " Full-Scale Testing of Wutcr Mist Fire Extinguishing Systems for Machinery Spaces on US Army Watercraft," NRL Ltr Rpt Ser 6180/0692A.1, Washington, DC. 1 Dec. 1995.
24. Leonard, J. T., Back. G. G.. DiNenno. P. J., and Cummings, W. M., "Preliminary Ship Impact Study for Machinery Space Water Mist Total Flooding Systems,' ' NRL Ltr Rpt Ser 6180/0550.2, Washington, DC, 29 Dec. 1994.
25. Rosenblatt & Son. Inc., " Water Mist Delivery System Feasibility Design," prepared for Naval Sea Systems Command SEA 03G2, July 28, 199.5.
26. Williams. F. W., Street, T. T., Back, G. G.. Darwin, R. L., DiNenno, P. J., Steinberg. R. L., Hill. J. A., and Karlsen. J.. "Water Mist System: LPD-17 Design Validation and Full-scale Machinery Space Water Mist Fire Suppression Tests," NRL Ltr Rpt Ser 6180/0007, Washington, DC, 16 Jan. 1997.
27. Back, G. G., and Williams, F. W., "Full Scale Evaluation ofthe Water Mist Additive QUAD-EX,'' NRL Ltr Rpt Ser 6180/0027, Washington. DC, 29 Jan. 1997.
28. Back, G. G., DiNenno. P. J., Williams, F. W., and Farley, J. P., " Water Mist System Nozzle Development Tests," NRL Ltr Rpt Ser 6180/0017, Washington. DC, 03 Feh. 1997.
29. Back, G. G., Williams, F. W., DiNenno, P. J., Farley, J. P.. Hill, S. A., Darwin. R. L., Toomey, T. A., Havlovich, B. J., "Full-Scale Machinery Space Water Mist Tests: Final Design Validation," NRL Ltr Rpt Ser 6180/0077, Washington, DC, 24 Feb. 1997.

30. Darwin, R. L., " Water Mist Systems For US Navy Ships," *Proceedings*, Halon Options Technical Working Conference, Albuquerque, NM, pp. 516-527, 1997.
31. Bernstein, R. I., " LPD- 17 Water Mist System Nozzle Location Guidebook," M. Rosenblatt & Son, Inc., May 6, 1998.
32. Back, G. G., DiNenno, P. J., Darwin, R. L.. Hill, S. A., Williams, F. W., Farley, J. P., Havlovich, B. J., Toomey, T. A., " Full-scale Machinery Space Water Mist Tests: Final Design Validation," Feb. 11, 1999.
33. Ndubizu, C. C., Ananth, R., Tatem, P. A., " Preliminary Experiments on the Water Mist Suppression of Gaseous Diffusion Flame." NRL Ltr Rpt Ser 6180/0188, Washington, DC, 24 April 1997.
34. Parker, A. J., Budnick, E. K., Williams, F. W., " Sensitivity of Operational Parameters for Low Pressure Water Mist Systems in Residential Type Fires," NRL Ltr Rpt Ser 6180/0246, Washington, DC, 18 June 1997.
35. Prasad, **K.,** Li, C., Kailasanath, K.," Numerical Modeling of Fire Suppression Using Water Mist. 2. An Optimization Study on Jet Diffusion Flames," NRL Ltr Rpt Ser 6180, Washington, DC, June 22, 1998.
36. Back, G. G., and Beyler, C. L., "A Model for Predicting Fire Suppression in Spaces Protected by Water Mist Systems," presented at the Society of Fire Protection Engineers Seminar NFPA Annual Meeting, 19 May 1997.
37. Gauthier Jr., L. R.. Bennett, J. M., Land III, H. B., "The Effects of Water Mist Discharge on Energized LPD 17 Electrical Equipment in the Absence of Fire - Initial Studies," Test Report AATDL-99-024, The Johns Hopkins University Applied Physics Laboratory, *29* Jan. 1999.
38. Back, G. G., Williams, F. W., Darwin, R. L., Sheinson, R. S., Maranghides, A., "Self-Contained Water Mist Literature Search," NRL Ltr Rpt Ser 6180/0471, Washington, DC, 10 Sept. 1998.
39. Maranghides, A., and Sheinson, R. S., "Test Plan for Self-contained Total Flooding Halon 1301 Alternative Technologies Evaluation - Phase I, Marioff Hi-Fog Water Mist System,'' NRL Ltr Rpt Ser 6180/0108, Mar. 11, 1999.
40. Ryan, D. F., "Procurement Specification **for** the Medium Pressure Palletized Small Water Mist Fire Suppression System," M. Rosenblatt & Son, Inc., Mar. 15, 1999.
41. Mawhinney, J., DiNenno, P. J., Williams, F. W., "Water Mist Flashover Suppression and Boundary Cooling System for Integration with DC-ARM: Summary of Testing," NRL Ltr Rpt Ser 6180/0001A, Washington, DC, Feb. 4, 1999.